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ABSTRACT

This paper outlines a model of learning and problem solving based on ideas derived from information processing models of memory and Ausubel's theory of meaningful learning. The model explicitly deals with the cognitive processes that are required for learning, and defines the conditions necessary for learning as the existence of relevant background knowledge in cognitive structure, and the capacity to integrate new knowledge with existing relevant knowledge in cognitive structure. This capacity is discussed in terms of various cognitive processes identified both by models of human memory and theories of human problem solving. To test the model, a research study was designed and carried out on 96 college students. The results of the study supported the model and are presented in the paper. (Author/GA)

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COGNITIVE FUNCTIONING: A MODEL FOR LEARNING AND PROBLEM SOLVING*

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Cognitive Functioning: A Model for Learning and Problem Solving

As an extension of the ideas of meaning and cognitive structure developed in the second paper of this set, this paper will outline a model of learning and problem solving based on ideas derived from information processing models of memory and Ausubel's theory of meaningful learning.

A key element of Ausubel's theory of meaningful learning is the effect of existing cognitive structure on new learning. Ausubel states that for new learning to occur new knowledge must be integrated with existing relevant background knowledge (subsumers). However, Ausubel fails to explicitly describe the cognitive processes whereby new knowledge becomes integrated with existing cognitive structure. This is seen as a weakness of Ausubel's theory.

By drawing on ideas from information processing models of memory and problem solving, a model of learning and problem solving will be developed that explicitly deals with the cognitive processes that are required for learning. The model defines the conditions necessary for learning as:

1. existence of relevant background knowledge in cognitive structure, and
2. the capacity to integrate new knowledge with existing relevant knowledge in cognitive structure.

The capacity to integrate new knowledge with existing relevant knowledge in cognitive structure will be discussed in terms of various cognitive processes identified both by models of human memory (Lindsay and Norman, 1977) and theories of human problem solving (Newell and Simon, 1972).

In support of the model, results of a research study designed to test the model will be presented.

Cognitive Functioning: A Model for Learning and Problem Solving

The purpose of this paper is twofold. First, I will briefly present a model of learning and problem solving based on information processing models of memory (Lindsay and Norman, 1977) and problem solving (Newell and Simon, 1972). This model of learning and problem solving is considered to be consistent with Ausubel's theory of meaningful learning (Ausubel, 1968) in that it stresses the importance of the effect of existing knowledge on new learning. However, this model is considered more adequate than Ausubel's theory in that it takes into account both the role of existing knowledge in learning and the cognitive processes by which new knowledge is integrated with existing knowledge. Second, the results of a study designed to test the model will be discussed.

Our main complaint against Ausubel's theory is not that he does not consider new learning to involve integration of new knowledge with existing knowledge....

> The differentiated cognitive content resulting from the meaningful learning process, and constituting its meaning, is an interactional product of the particular way in which the content of the new proposition is related to the content of relevant established ideas in cognitive structure (Ausubel, 1968, p. 52).

....but that he does not specifically develop or explicate the nature of the integrative process. Whether Ausubel intends it or not one tends to walk away from a reading of Ausubel considering existing knowledge and its organization as the only important variable in determining new learning.

There is no doubt that existing relevant knowledge and the organization is a primary determinant of meaningful learning. Consider the following representations[1] of two different organizations of knowledge regarding polar compounds (Figures I and II).

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[1] See Stewart, 1978 for a detailed discussion of the advantages of the use of semantic networks (representations) for the representation of cognitive structure.

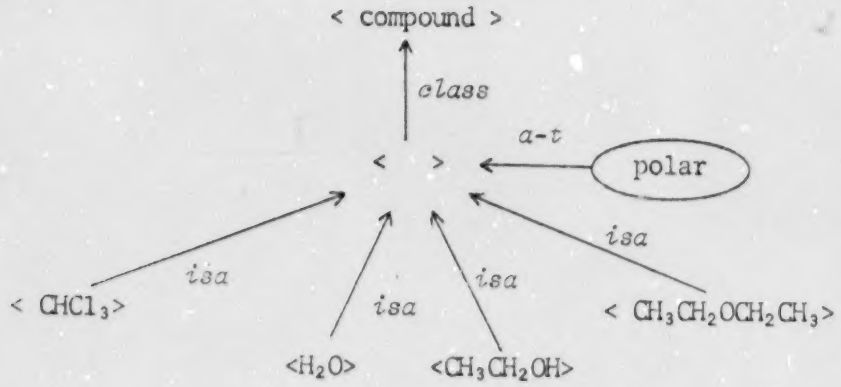

Figure 1 Semantic representation for polar compounds

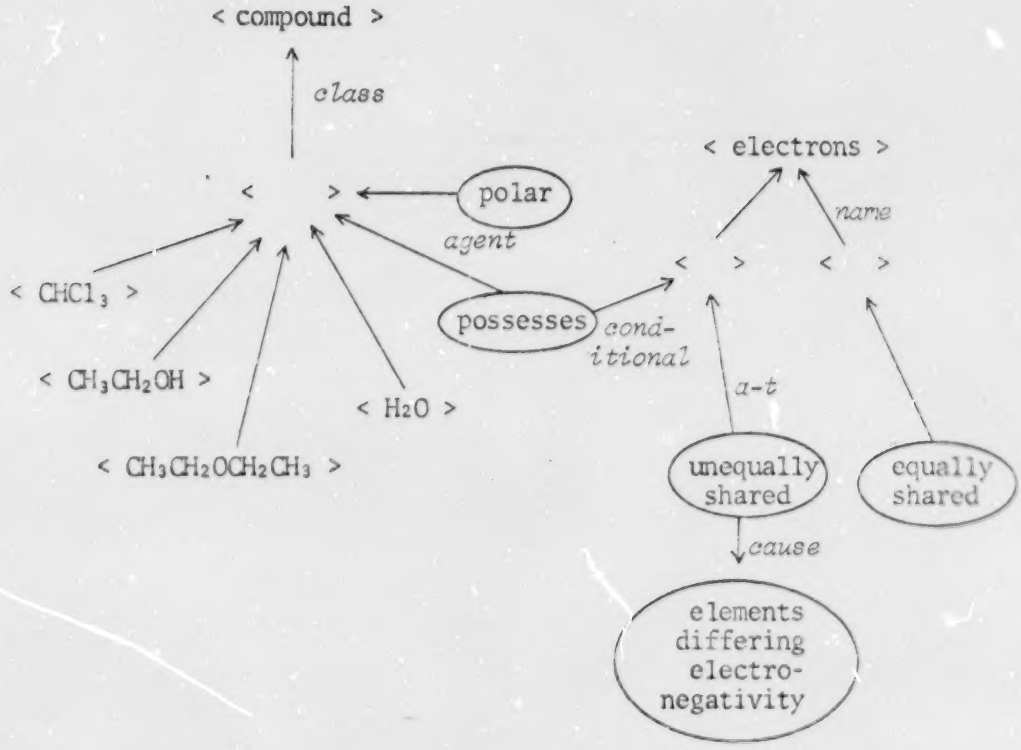

Figure II Semantic representation for polar compounds - electronegativity of elements included

The individual with the knowledge structure shown in Figure I knows that: "Chloroform ($CHCl_3$), water (H_2O), ethanol (CH_3CH_2OH) and ether ($CH_3CH_2OCH_2CH_3$) are polar molecules". On the other hand the individual with the knowledge structure shown in Figure II knows that polar molecules result from an uneven sharing of electrons between atoms and, in turn, that unequal sharing of electrons is due to different electronegativities of the bonding atoms.

How do each of these individuals process incoming information? How does the knowledge structure itself influence new learning? Consider if these two individuals were to receive the following new information— "H_2S, hydrogen sulfide, is a polar molecule". There is little that the knowledge structure of individual I allows save adding the new compound to his list of polar compounds. Individual II, however, can reconcile this new information with his existing knowledge by determining whether in fact S and H have different electronegativities. Whether or not individual II actually does integrate the new information with his existing knowledge structure does not follow directly from the structure of the existing knowledge—the existing knowledge structure presents the potential for integration of the new information but it does not assure it.

Nor does the existence of an appropriate knowledge structure necessarily imply that existing knowledge can be successfully used in solving problems. Take the case of an individual who possesses knowledge in memory that can be represented as in Figure III. If such an individual is asked "Is molecular oxygen a polar compound?", it seems that it is quite possible that all of the information contained in such an area of memory may not be taken into account when the individual answers the question. For example, the individual may generalize, seeing that many polar compounds contain oxygen, and answers, "Yes"; or perhaps, "I don't know". But, if someone were to intervene and effectively cue the integration of all knowledge in the particular area of memory with the incoming question the outcome might be very different:

A. Is oxygen (O_2) a polar compound?

B. Yes, I think so-it contains oxygen.

A. But wait a minute, What's a polar compound?

B. It's a compound that has unequally shared electrons.

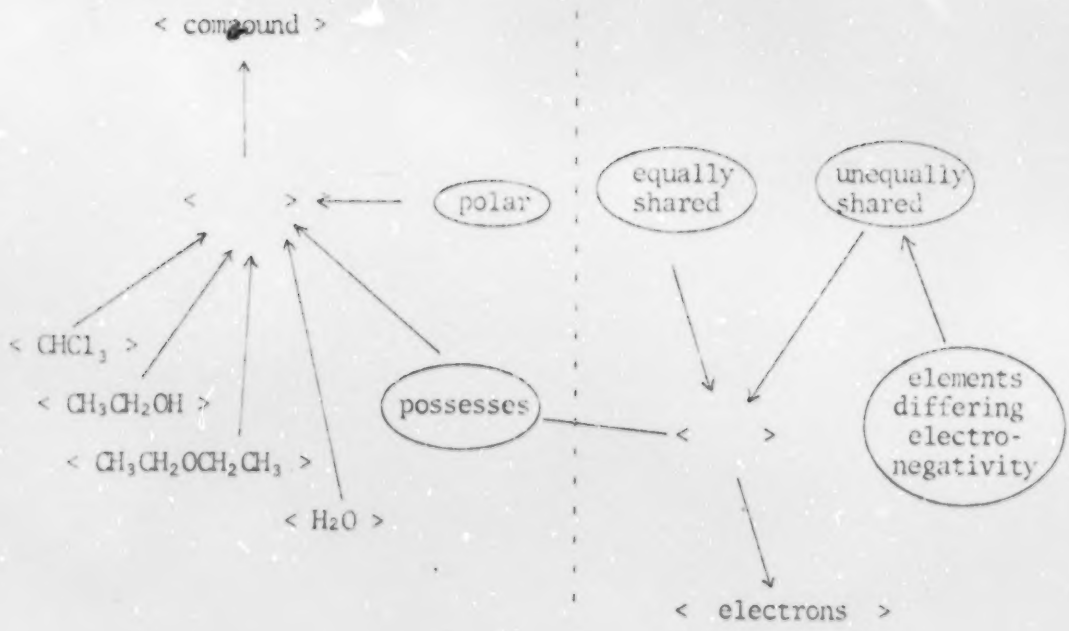

Figure III. Semantic network for knowledge about polar compounds [a]

a. The semantic network shown is only intended for example. I do not wish to imply that it contains all relevant information concerning polar compounds. The point is to show that even if an individual does have the knowledge represented here, and does hold the knowledge in memory in a highly similar structure all of the knowledge may not be utilized in answering simple questions and problems.

A. How come a compound has unequally shared electrons?

B. Well, if the elements have different electronegativities one element will have a greater share of electrons.

A. Does oxygen (O_2) contain elements with different electronegativities?

B. No-oh, it can't be a polar compound even though it contains oxygen! I never thought of that.

Why did the individual "never think of that"? It appears that given an adequate knowledge structure successful problem solving and meaningful learning will not occur unless the new knowledge is actively integrated with the existing knowledge structure. It appears that there exists another component to cognitive functioning—a capacity to integrate new knowledge—that is not solely a function of the existing knowledge nor its organization.

The capacity to integrate new knowledge with existing knowledge can be defined in terms of the cognitive control processes identified by information processing models of memory-the monitor, interpreter and manipulative rules of Lindsay and Norman's model of memory (see Van Kirk, 1978 and Atkin 1977 for more detailed discussion). Newell and Simon's (1972) work on human problem solving can also be expressed in terms of similar cognitive control processes. An in depth discussion of their work cannot be given here(see Atkin, 1977 for more detailed discussion), however I will attempt to summarize the aspects of problem solving described by Newell and Simon in terms of the information processing model of Lindsay and Norman:

1. A problem space is set up that is an individual's internal representation of the task; it will, in part be defined by the task environment but will also reflect the individuals past experience and related knowledge in long-term memory. Just as adding information to long-term memory required activation of the appropriate area of long-term memory, so too does setting up a problem space. In the information processing model of memory activation of the appropriate area of memory was the function of the monitor. It appears that setting up a problem space will be under the control of this same monitoring system-the task environment is interpreted and an appropriate area of long-term memory is activated.

2. The problem is far from being solved when the problem space has been set up. Promising areas of the problem space are chosen to be operated on-heuristic methods are used to identify the promising areas. Just as the interpreter functioned to view the data base in adding information to, and retrieving information from long-term memory, in problem solving the interpreter reduces the search in the problem space by identifying appropriate heuristic methods for manipulating the information contained in the problem.

3. Once operators or plans are identified, they are applied and the subsequent information obtained defines a new knowledge state. This new knowledge state can be further operated on in the process of reaching a solution. Thus, the information contained in the task environment is integrated with existing information in memory. In the information processing model of memory this aspect of the cognitive processes involved in adding new information to memory is essentially execution of the manipulative rules.

4. The major limitations on human problem solving are the limitations of the information processing system: (1) its limited short-term memory (external memory aids such as writing information down are often necessary), and (2) the serial nature of its processing (only one event can be processed in short-term memory at any time).

Just as in addition of knowledge to memory, there are several ways in which the control processes of problem solving can fail to produce a solution to the problem. An inappropriate problem space may be chosen and the monitoring system is not aware of its mistake or an inadequate data base is all that is available; heuristic methods may not be made available to the individual to reduce the search of the problem space or if they are made available they may be inappropriate (malfunctioning of the interpreter); operations may be incorrectly applied or inappropriately chosen, and finally the problem itself may require processing that is beyond the capacity of human short-term memory, even when external memory aids and symbol substitutions are used.

From this discussion, it appears that there is a good deal of correspondence

between the control processes involved in problem solving and the control processes required for meaningful learning. In order to clarify the nature of the correspondence between problem solving and meaningful learning consider what is involved in solving the following two problems:

1. Is molecular oxygen a polar compound?
2. A man is looking at a portrait on a wall and says: Brothers and sisters have I none, but that man's father is my father's son. Who is the portrait of?

These problems are different in that one requires retrieval of a greater amount of information from long-term memory and in that the information to be retrieved differs in the degree to which it is commonly used, but they are similar in that the requirements they place on the manipulative processes of the information processing system are similar. To illustrate this point, consider what would be involved in solving the two problems if all the information necessary to solve both problems was printed out on a sheet of paper and then presented to an individual. Since all the information required to solve the problems is on paper (that is all the information concerning polar compounds, molecular structure, etc. for problem I and definitions of brothers, sisters father etc. for problem 2) all that is required to solve the problem is manipulation of the information to reach a solution. Whether the information comes from long-term memory or from an external source, the cognitive processes required in manipulating the information to reacha solution are similar.

I have attempted to show that there is a correspondence between the processes ofsolving "subject-matter-free"[1] problems and the processes involved in solving a chemical problem-a subject-matter-rich problem. But what does this correspondence have to do with learning?

It is my contention that the cognitive control processes involved in integrating new knowledge with existing knowledge, and the cognitive control processes involved in solving problems using existing knowledge are one and the same. Consider Figure IV in which I have diagrammed the three processes under consideration: (1) learning of new

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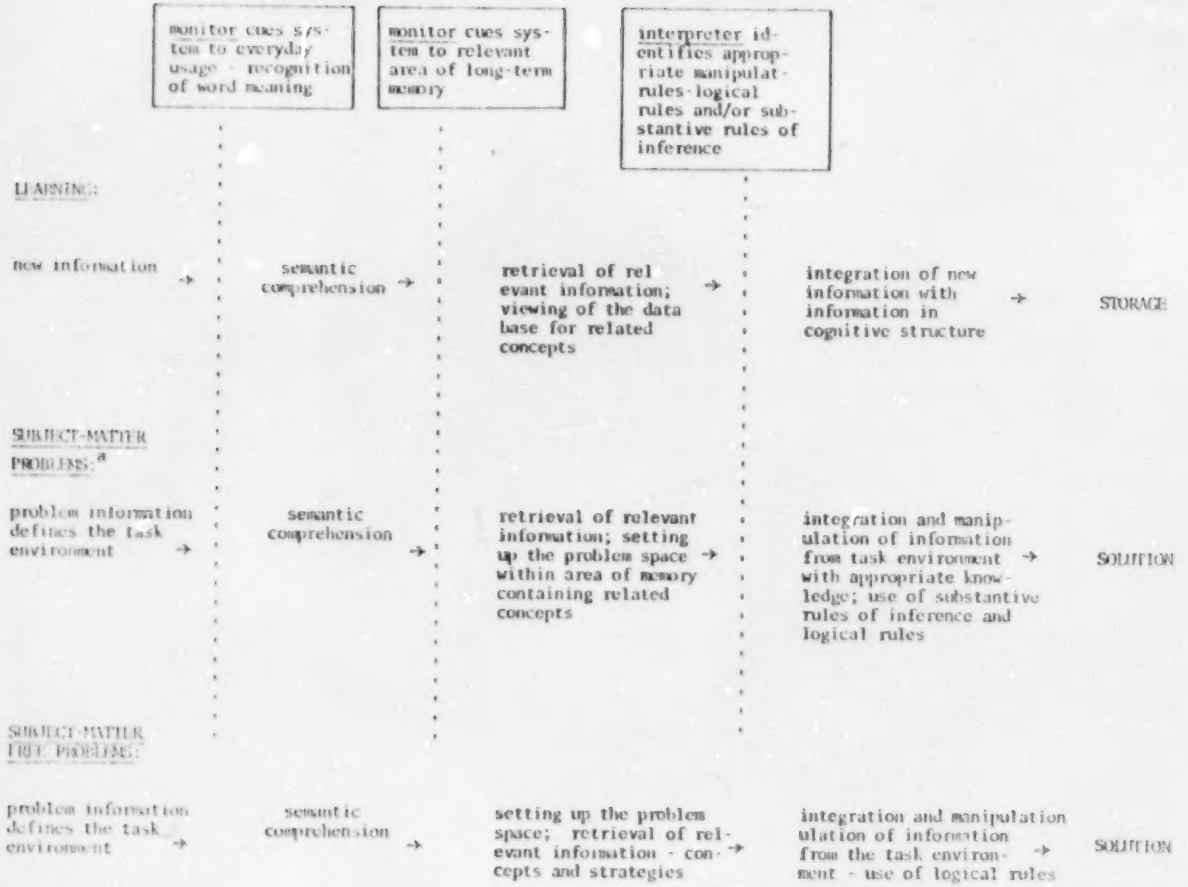
1 By subject-matter-free problems I mean problems that do not require specialized disciplinary knowledge for a solution to be reached. That these problems do not require subject-matter knowledge does not imply that subject-matter knowledge might not be useful in solving them-e.g., the recognition of analagous problems in a discipline would surely aid the problem solving process.


monitor cues s/system to everyday usage - recognition of word meaning
monitor cues system to relevant area of long-term memory
interpreter identifies appropriate manipulat-rules-logical rules and/or substantive rules of inference
LEARNING:
new information
semantic comprehension
retrieval of relevant information; viewing of the data base for related concepts
integration of new information with information in cognitive structure
STORAGE
SUBJECT-MATTER PROBLEMS:[a]
problem information defines the task environment
semantic comprehension
retrieval of relevant information; setting up the problem space within area of memory containing related concepts
integration and manipulation of information from task environment with appropriate knowledge; use of substantive rules of inference and logical rules
SOLUTION
SUBJECT-MATTER FREE PROBLEMS:
problem information defines the task environment
semantic comprehension
setting up the problem space; retrieval of relevant information - concepts and strategies
integration and manipulation of information from the task environment - use of logical rules
SOLUTION

a. Subject matter problems may be simple or complex. Simple problems require use of knowledge in a manner similar to the way in which the information was stored and thus require minimal activation of the manipulative rules. Complex problems, on the other hand, require re-manipulation of information in memory and thus are like learning in the demands they place on the control processes.

Figure IV

and (3) solving subject-matter-free problems. The role of the monitor in comprehending the meaning of the presented information, be it in problem form or not, is constant over the three tasks. Similarly, the role of the monitor in cueing the system into the relevant area of long term memory is also constant — the only difference over the three tasks, for this step in the processing system, is that for subject-matter-free problems the information to be retrieved is not subject-matter specific, while for the other two tasks the information to be retrieved is subject matter specific.

The role of the interpreter too, is essentially the same for the three processes. The particular heuristic methods identified by the interpreter for the two different types of problem solving are somewhat different since for the subject matter problems the heuristic methods will reflect the strategies of problem solving within the particular subject-matter area while, for the subject matter free problems, the heuristic methods will be more general in nature.

From Figure IV one can see that the information processing model of learning and problem solving describes many aspects of the learning and problem solving process-comprehension of the new information, activation of the appropriate area of memory and active integration of the new information with existing knowledge in the activated area. Thus, meaningful learning can be seen to occur when (a) one has an appropriate cognitive structure, and (b) one has a capacity to activate this area of knowledge and subsequently integrate the new information within it. This model of learning and problem solving defines this capacity in terms of the control processes of the information processing system—in terms of the correct functioning of the monitor and interpreter.

Experimental Study

According to the information processing model outlined above, meaningful learning may fail to occur for two reasons. If appropriate knowledge does not exist in cognitive structure meaningful learning cannot occur. But even if the appropriate knowledge does exist in cognitive structure, meaningful learning will not occur unless the control processes whereby the appropriate knowledge is activated, searched and integrated with the incoming information are carried out. It is likely that individuals vary in their ability to correctly activate these control processes.

If indeed the processes of learning and problem solving are related, and successful problem solving can be viewed in terms of correct activation of the cognitive control processes, a high correlation between problem solving ability and successful meaningful learning of subject matter should be observed. Furthermore, it stands to reason that an instructional treatment that explicitly guides the control processes required for meaningful learning should result in a higher degree of meaningful learning than an instructional treatment that requires the learner to perform these processes unaided. This effect should be most marked for those individuals of low problem solving ability.

Thus, may two major hypotheses are:

1. (a) There is a correlation between an information processing ability, as exhibited in the successful solving of subject-matter free problems, and the meaningful learning of new information.
   (b) Problem solving ability has predictive power over and above that of degree of relevant prior knowledge with regard to meaningful learning.
2. There is an interaction between problem solving ability and instructional treatment when the treatments being compared differ in the degree to which they guide the cognitive control processes necessary for meaningful learning.

The theoretical relationships that I am predicting are shown in Figure V. The experimental design for the study is set out in Figure VII. For further discussion of the experimental study and its instigation see Atkin (1977).

The study was carried out on 96 sophomore and junior students chosen from a sample population of 330 students enrolled in a one semester course in organic chemistry at Cornell University. The students were rated on their problem solving ability (measure of integrative capacity) and prior knowledge of background concepts (knowledge structure). From the 96 students tested two subsamples were chosen which were matched on both problem solving and prior knowledge - Figure VIII.

The topic chosen for the instructional treatment was the Benzyne Mechanism of Nucleophilic Aromatic Substitution. Treatment 0 (not designed to aid the

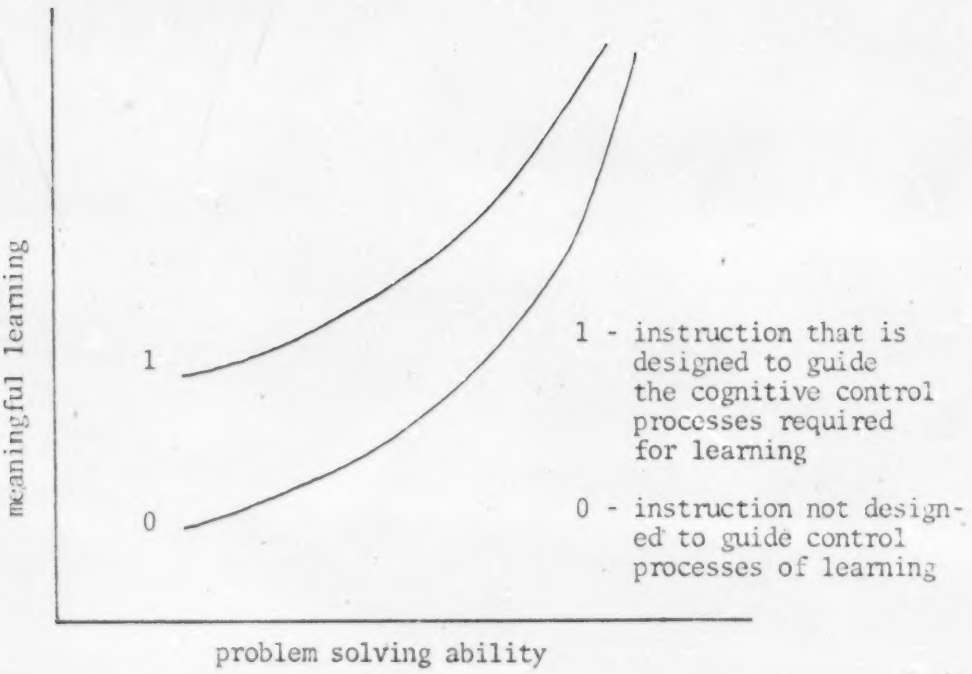

meaningful learning
1
0
problem solving ability
1 - instruction that is designed to guide the cognitive control processes required for learning
0 - instruction not designed to guide control processes of learning

Figure V Predicted relationship between problem solving ability and meaningful learning of organic chemistry

5 - set up the appropriate problem space(several may have been tried in selecting the appropriate one) without assistance from the experimenter; successfully operated within it to obtain a solution.

4 - set up an appropriate problem space without assistance; error(s) in manipulative rules incurred but when assisted by the experimenter continued to solve the problem without further help; heuristic methods not always used.

3 - received some guidance in two of the three aspects of problem solving behavior identified

2 - received guidance in all three aspects of the problem solving procedure but could work actively towards a solution as long as guidance was given

1 - could not work actively, alone, towards a solution even after having received assistance in all three aspects of solving the problem; could only understand the solution following detailed explanation by the experimenter

Figure VI Rating scale used for the problem solving task

EXPERIMENTAL STUDY

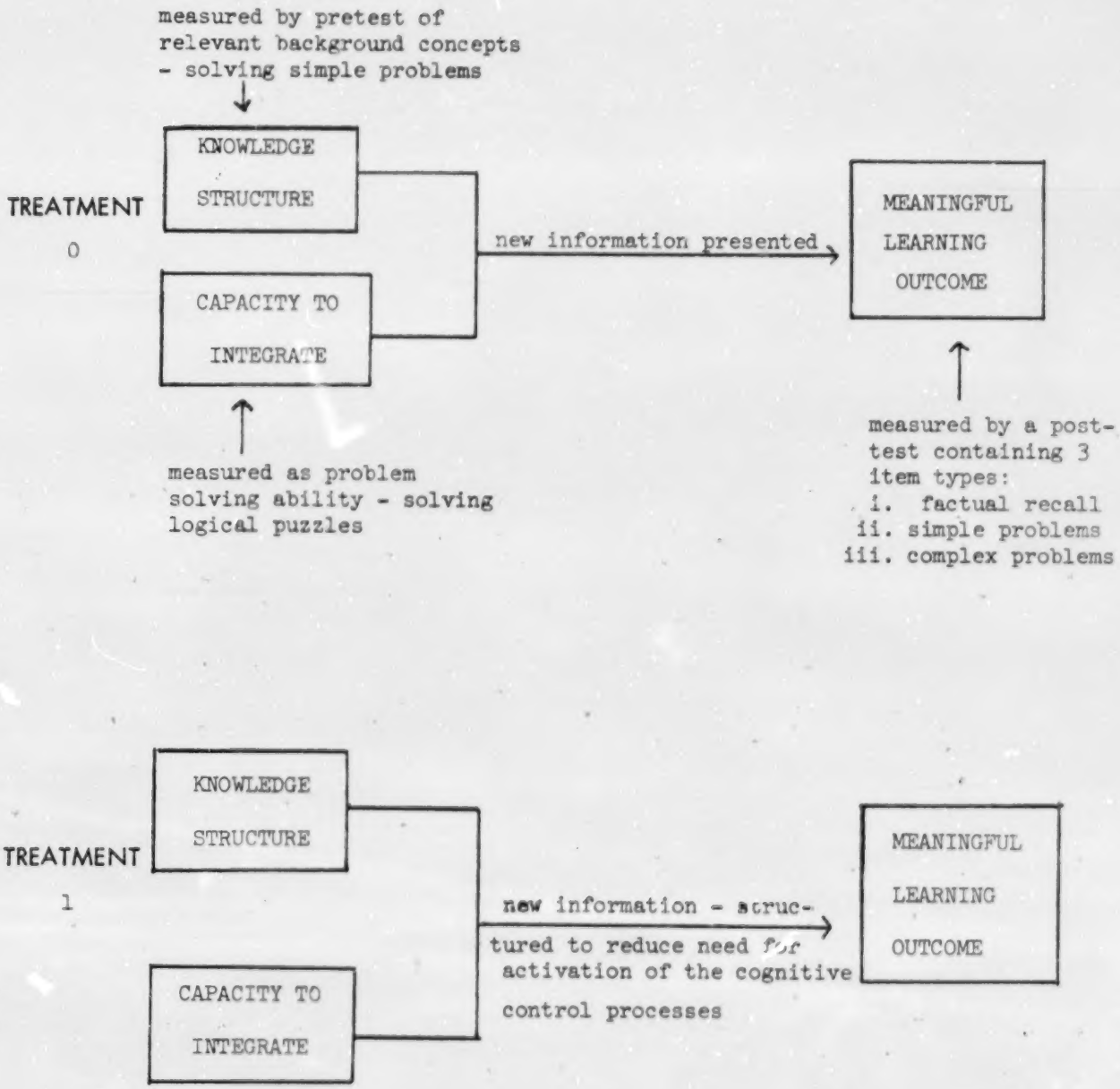


Figure VII

cognitive control processes) was taken from a standard textbook[1] in organic chemistry. Care was taken to ensure that the factual knowledge contained in treatment 0 was identical to the factual knowledge in treatment 1. Treatment 1 was specifically designed to aid integration of the new information. From the model of learning and problem solving presented it can be seen that designing a treatment to guide the integrative processes would involve:

(i) providing a cue to the monitor system as to the relevant area of knowledge in memory; (ii) specifically interpreting the meaning of the new information in terms of the area of knowledge identified, and (iii) actively applying appropriate manipulative rules and engaging the learner in the execution of these rules.

The posttest which was used to measure the meaningful learning outcome incorporated three different types of test items:

Type 1 (PTI): tested for factual recall. A correct answer to these items did not necessarily indicate rote memorization but the maximum score could be obtained as a result of rote memorization.

Type 2 (PT 2): tested for meaningful learning since the problems had not been encountered by the subjects previously. These items tested for application of the new information (as well as recognizing when the newly learned ideas did not apply) by the presentation of simple problems.

Type 3 (PT 3): tested for application of the newly learned information in the form of a complex problem.

Results

The results from the experimental study support the hypotheses stated earlier.

Hypothesis 1 (a) There is a correlation between an information processing ability and the meaningful learning of organic chemistry.

If hypothesis 1(a) is correct, the correlation between the posttest scores for the Type 2 items (PT 2) and problem solving (PS) would be expected to be

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[1] Streitweiser, A. Jr., and Heathcock, H.H., Introduction to Organic Chemistry, New York: Macmillan, 1976.

significantly different from zero. Since the type 3 item (PT 3) was a complex problem that involved reorganizing the newly learned information, one would also expect from hypothesis 1(a) that the correlation between PT 3 and PS should similarly be significantly different from zero. The appropriate treatment group to consider in order to test hypothesis 1(a) is treatment group 0 since this treatment was not designed to enhance maningful learning for those individuals low on problem solving. The correlation between PT 2 and PS for treatment group 0 is: $r = 0.91$. The correlation of PT 3 with PS is: $r = 0.81$. Both of these correlations are significantly different from zero ($p < 0.01$) and thus hypothesis 1(a) is accepted.

Hypothesis 1 (b) Problem solving ability has predictive power over and above that of prior knowledge with regard to meaningful learning of organic chemistry.

Before considering evidence in support of this hypothesis, consider what would be the case if PS was highly related to prior knowledge (PK). It could be that the high correlation between PS and PT 2 is simply due to the fact that there is a high correlation between PK and PT 2 (this is essentially Ausubel's viewpoint). Thus, it is important to establish the correlation of PS, alone, with PT 2. To do this one needs to consider a group of subjects having the same PK but with different PS abilities. This can be achieved statistically by determining the correlation of PT 2 with PS, with PK partialled out. This partial correlation squared gives a measure of the amount of variance in PT 2 socres explained by PS after the variance due to PK has been taken into account.

The partial correlations of PT 2 with PS (PK partialled out) for treatment 0 is: $r = 0.88$; $r^2 = 0.78$. Thus, after the variance due to PK has been taken into account, 78% of the remaining variance is explained by PS On the basis of these results, hypothesis 1(b) can be accepted.

So far I have been concerned with evidence that supports hypothesis 1— that there is a relationship between the processes of successful problem solving and the processes of meaningful learning. Having seen that there is a large positive correlation between PS and meaningful learning as measured by PT 2, even after the variance due to prior knowledge has been taken into account, it remains to be seen if treatment 1 (designed specifically to reduce the effect of problem solving ability) significantly reduced the correlation between PS and PT 2.

Hypothesis 2 There is an interaction between problem solving ability and instructional treatment when the treatments being compared differ in the degree to which they guide the cognitive control processes necessary for meaningful learning.

The correlation obtained for PT 2 with PS for treatment 1 is: $r = 0.64$; $r^2 = 0.41$ while for treatment 0 the correlation between PS and PT 2 is $r = 0.91$ $r^2 = 0.83$. In treatment 1 only 41% of the variance in meaningful learning outcome is explained by PS while for treatment 0.83% of the variance in the meaningful learning outcome is explained by PS Again, it is perhaps more telling to compare the partial correlations of PS with PT (PK partialled out) for the two groups (Table II). For treatment 0: $r = 0.88$; $r^2 = 0.78$ and for treatment 1: $r = 0.54$; r^2 0.29. This interaction between problem solving ability and instructional treatment is plotted in Figure X.

Despite the significant difference in the correlations of PT 2 with PS for the two groups, there is no significant difference in the correlations of PT 3, the complex problem, with PS for the two groups. For treatment 1 the correlation of PT 3 with PS is: $r = 0.85$; $r^2 = 0.72$ while for treatment 0 the correlation of PT 3 with PS is: $r = 0.81$; $r^2 = 0.66$. Thus, it appears that although treatment 1 enhanced meaningful learning, those low with respect to problem solving ability still had difficulty in using the newly learned information to solve a complex problem. This result is in keeping with the model of learning and problem solving proposed since, from the model, it would not be expected that a low problem solver (low integrative capacity) should be able to solve a complex problem with the new information since by definition a complex problem requires further activation of the cognitive control processes. Since it was the very inability to successfully activate the appropriate control processes that resulted in a low score on problem solving, it would not be expected that such an individual could solve complex problems with the newly learned information. In fact, one of the main points of the model was to show that no matter how well organized knowledge in cognitive structure is, use of this knowledge in learning and complex problem solving will not occur unless the cognitive control processes are efficiently executed. Thus, the failure of treatment 1 to enhance complex problem solving is supportive of the model.

In summary, the experimental study described supports the model of learning and problem solving proposed and indicates that both the organization of knowledge in memory and a capacity to integrate incoming information with existing knowledge are important variables in considering individual differences in meaningful learning. The study also shows, that by aiding the cognitive control processes identified by the model as necessary for meaningful learning, meaningful learning of new information may be enhanced.

TABLE I Correlations of the posttest scores with problem solving ability

	TREATMENT 0		TREATMENT 1	
	PK	PS	PK	PS
PT 1	0.212	0.272	0.023	0.278
PT 2	0.498	0.910	0.469	0.637
PT 3	0.326	0.813	0.459	0.846

TABLE II Partial correlations for the posttest scores with problem solving ability - prior knowledge partialled out

	TREATMENT 0	TREATMENT 1
PT 1	$r = 0.232$; $r^2 = 0.054$	$r = 0.343$; $r^2 = 0.117$
PT 2	$r = 0.883$; $r^2 = 0.780$	$r = 0.535$; $r^2 = 0.286$
PT 12	$r = 0.892$; $r^2 = 0.796$	$r = 0.540$; $r^2 = 0.292$
PT 3	$r = 0.791$; $r^2 = 0.625$	$r = 0.804$; $r^2 = 0.646$
PTTOT	$r = 0.899$; $r^2 = 0.809$	$r = 0.842$; $r^2 = 0.842$

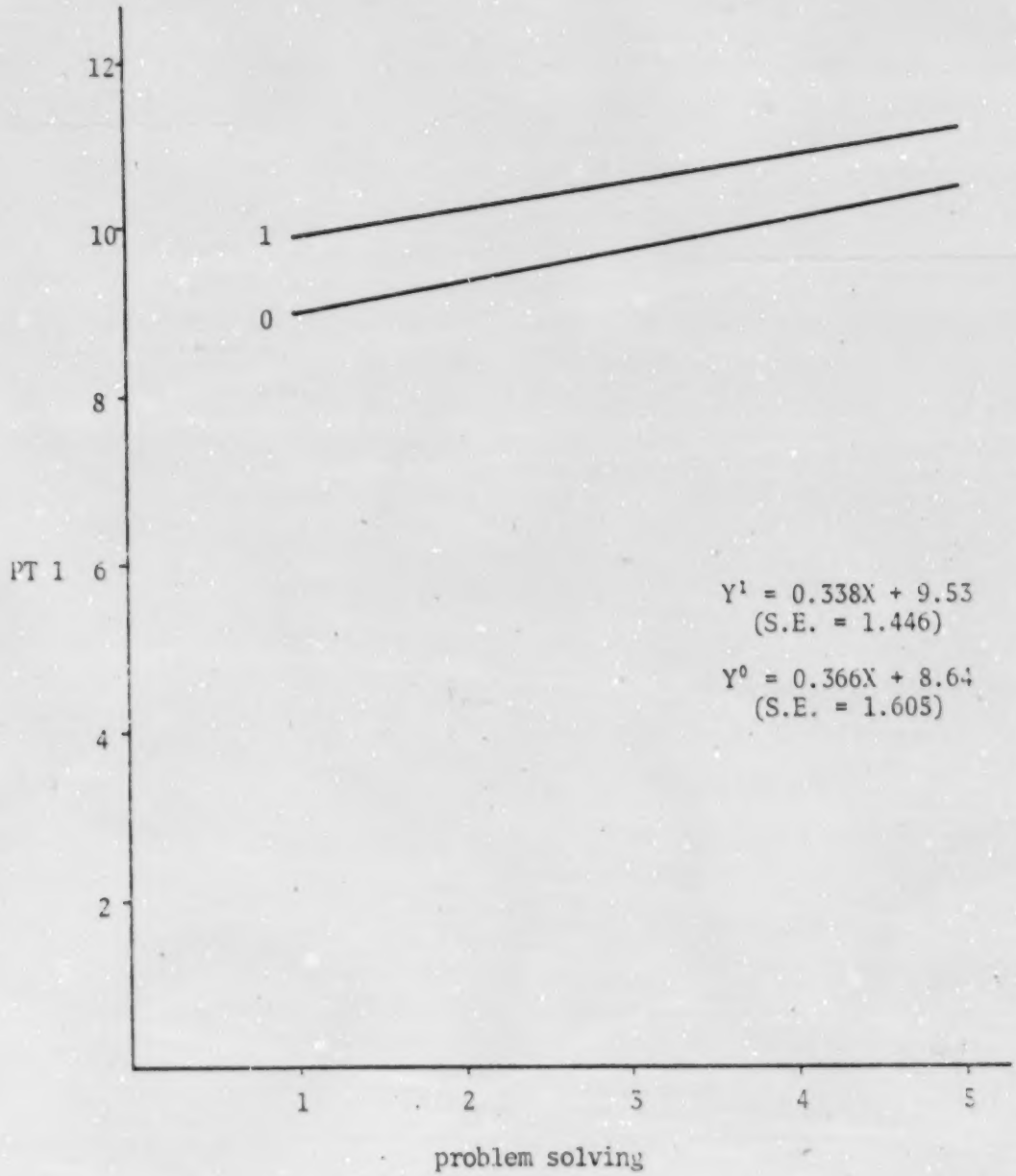

Figure IX Plot of separate regression equations for PT 1 versus problem solving - Treatment 1 and Treatment 0

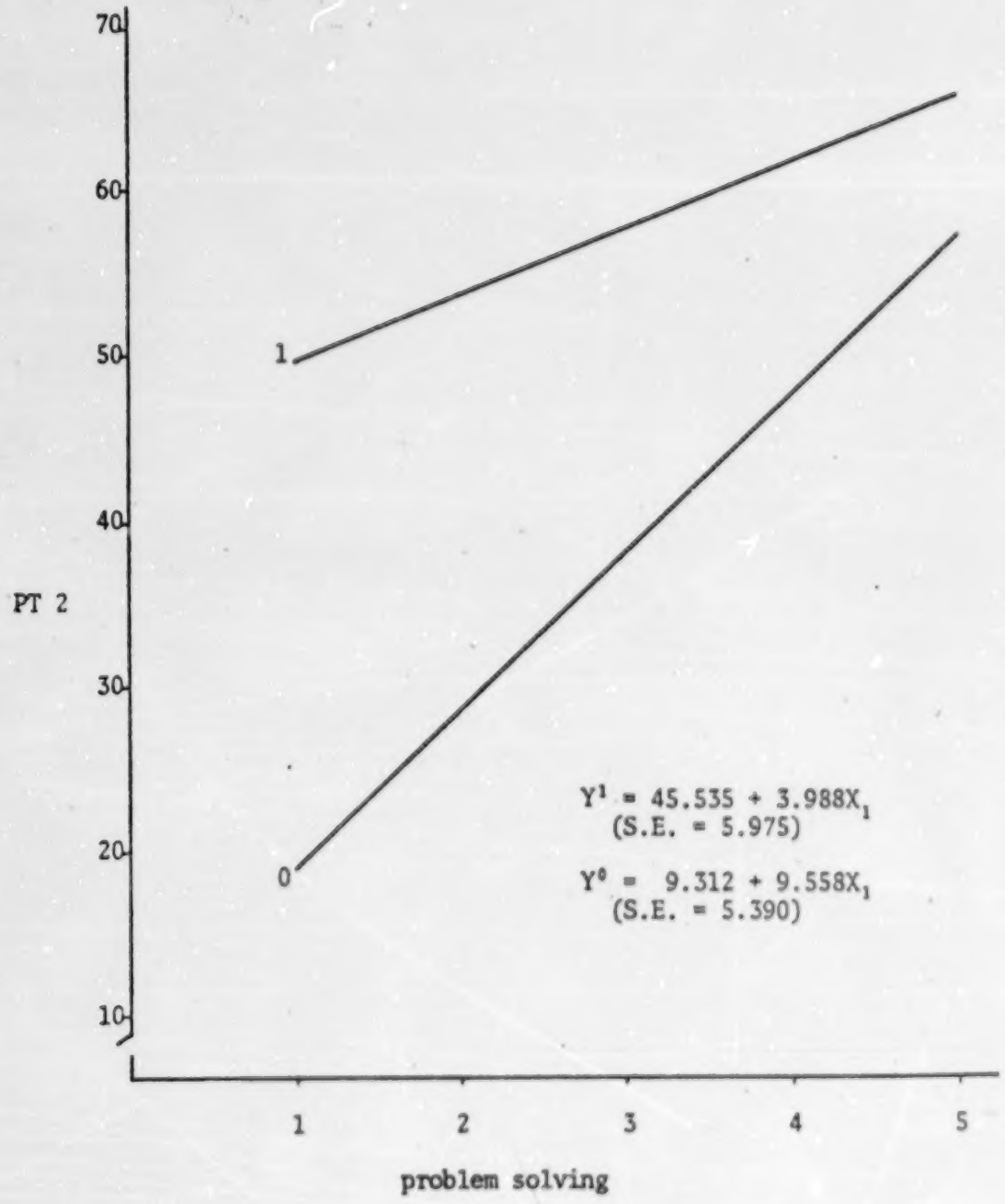

Figure X Plot of separate regression equations for PT 2 versus problem solving - treatment 1 and treatment 0

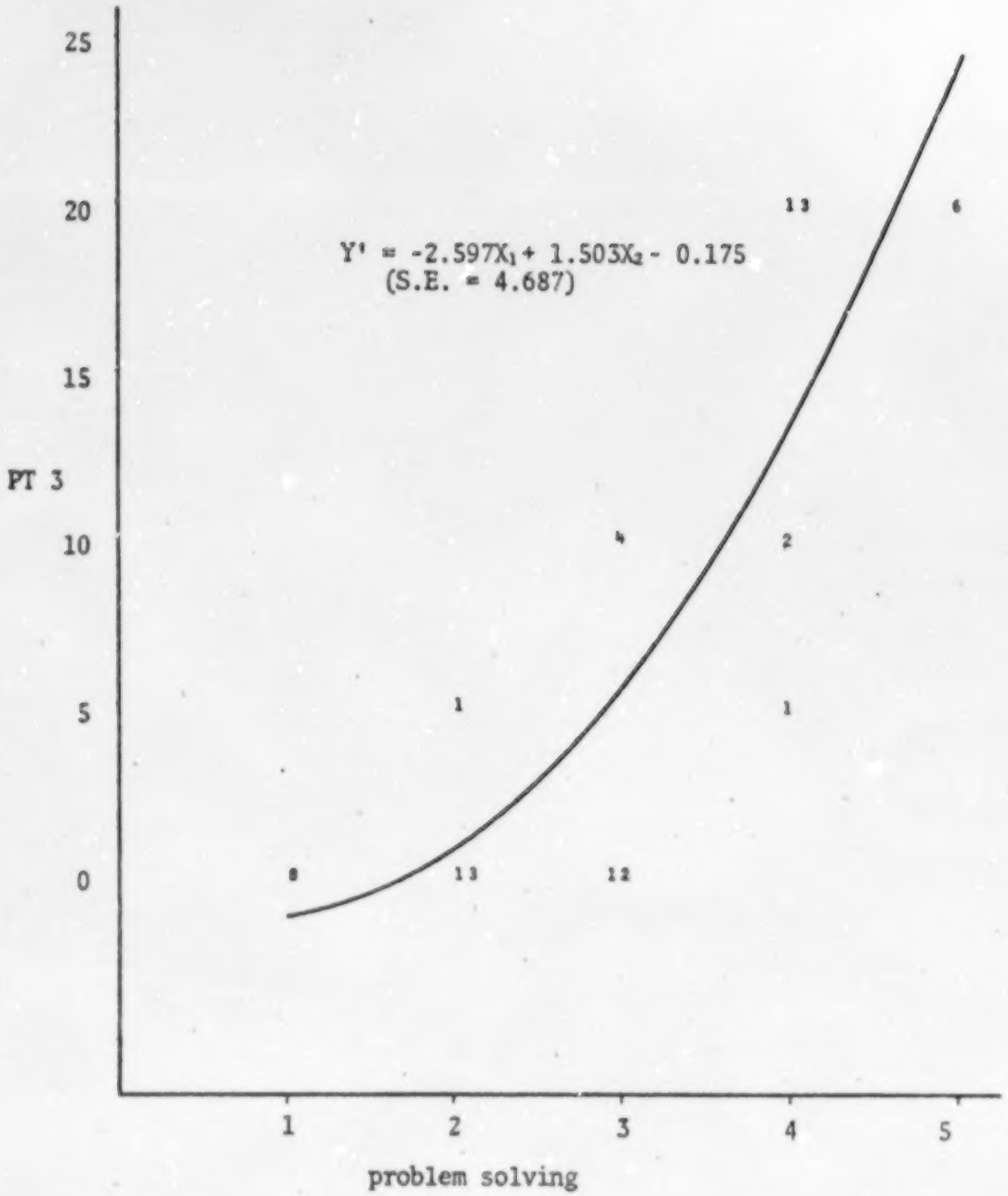

Figure XI Plot of regression of PT 3 on PS and PS^2 both treatments Plotted numbers represent the number of subjects scoring these particular values for PS and PT 3

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APPENDIX A

The Problem Solving Task

1. Three men are standing in a row like those in Figure 1.

   #1 cannot see the head of #2 nor of #3.

   #2 can see the head of #1 but not of #3.

   #3 can see the heads of #1 and #2.

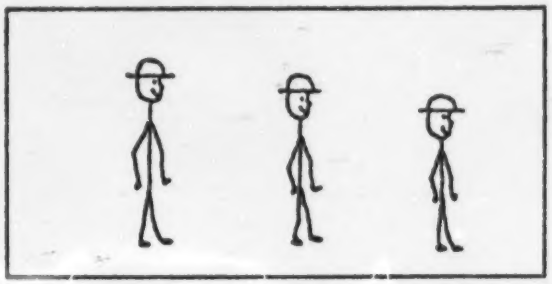

Figure 1.

Another person has five hats, three of which are white and two are black. The three men are blindfolded and the hats are mixed up. The person then selects three hats from the five and places one on each man's head. The remaining hats are then hidden from view and the blindfolds are removed. Each man does not know the color of the hat he is now wearing.

The person then asks each man in turn, 1,2 and then 3: *"Do you know the color of the hat you are wearing?"*.

Man #1 says; *"No, I don't know."*

Man #2 says; *"No, I don't know."*

Then, man #3 says; *"No, I don't know."*

The person then repeats the question to the three men again, in the same order as before.

Man #1 says; *"No, I don't know."*

Man #2 says; *"No, I don't know."*

And then man #3 says; *"No, I don't know."*

Once again the person repeats the question. This time man #1 says; *"Yes, now I know!"*

Assume that all of the men's answers are correct. Use the answers given by the three men to answer the following question.

What color hat must #1 be wearing? Why?

2. You have two piles of silver dollars. If seven dollars are transferred from the first pile to the second, the second pile becomes twice as tall as the first. On the other hand, if one had transferred seven dollars from the second pile to the first pile they would have become equal in height.

How many silver dollars do you have in each pile originally?

3. A man is looking at a portrait on a wall and says; *"Brothers and sisters have I none, but that man's father is my father's son."*

Who is the portrait of?

4. In a certain mythical population politicians always lie and non-politicians always tell the truth. A stranger approaches three members of the population and asks the first member: *"Are you a politician?"*

The first member gave an answer to this question, then the second member said: *"The first mamber denied being a politician."*. The third member then interjected and said: *"The first member is a politician."*.

How many of these three are politicians?